Laser Polarized Muonic Helium

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We have formed polarized muonic ^{3}He by stopping unpolarized negative muons in a gaseous ^{3}He target which was polarized by spin exchange with laser optically pumped Rb vapor. We measured P_μ^N, the resulting muon polarization normalized to the nuclear polarization of the ^{3}He. In addition to being a property that characterizes the muon cascade in the μ-^{3}He system, P_μ^N is of practical value for future experiments on nuclear muon capture. Our result, $P_\mu^N = 0.072 \pm 0.008$, is a factor of 2 smaller than predicted by simple atomic cascade theory.

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The physics of forming polarized muonic atoms and ions has proven to be a rich subject, particularly in the case of muonic helium. When a polarized beam of muons is stopped in helium gas, the residual polarization in the $1s$ state is measured [1–3] to be only about $\frac{1}{3}$ of the value expected from the established muon cascade theory [4–6]. This theory works well for most other atoms. It has been suggested [2] that the anomalously low polarization in helium is due to Stark mixing that occurs during collisions when the excited $(\mu^-\mathrm{He})^+$ ion is in states of high principal quantum number n.

Polarized muonic ^{3}He may also be produced through spin exchange with laser optically pumped Rb vapor. In the method demonstrated in this Letter, the polarization of the Rb is slowly transferred to the ^{3}He nuclei [7], resulting in a polarized target. Unpolarized muons stopped in the target become polarized during the cascade due to the hyperfine interaction with the nucleus. As was discussed by Kuno, Nagamine, and Yamazaki, in the absence of collisional depolarization the muon polarization upon reaching the $1s$ state depends only on the n level at which the hyperfine splitting becomes comparable to the level width [8]. In fact, we will show that depolarization due to collisions is important for muonic helium. We note that the idea of "repolarizing" muons by stopping them in a polarized target was first demonstrated for ^{209}Bi, in which the nuclear spins were oriented by placing a ferromagnetic compound BiMn in a magnetic field of 5–8 kG at temperatures of around 60 mK [9].

Nuclear physics provides important motivation for producing highly polarized muonic ^{3}He. For example, the spin dependence of the reaction $\mu^- + {}^3\mathrm{He} \rightarrow {}^3\mathrm{H} + \nu$ provides a clean way to measure the induced pseudoscalar coupling constant g_P for ^{3}He [10,11]. An experiment to measure g_P using a polarized μ^- beam was performed by Dugan, Wu, and collaborators [12,13], but had limited sensitivity due to the small asymmetries attainable with a polarized beam. Our laser techniques provide important advantages for such experiments. First, there are several ways to reverse the target spin, a vital feature for experiments that measure small asymmetries. Also, the target requires only small magnetic fields and ambient temperatures, allowing considerable flexibility in the design of the apparatus.

The experiment was performed at the stopped muon channel (SMC) of the Los Alamos Clinton P. Anderson Meson Physics Facility (LAMPF). The muons were stopped in spherical glass target cells, 2.5 cm in diameter, filled with approximately 8 atm ^{3}He, 75 Torr N_2, and several milligrams of Rb metal. (Pressures are quoted at 293 K.) The cells, made of Corning 1720 aluminosilicate glass, had walls with a thickness of about 100 μm. While in the beam, the target spin was aligned along a vertical magnetic "holding field," nominally 1–2 G, provided by a pair of Helmholtz coils. The ^{3}He was polarized by spin exchange with Rb vapor which was optically pumped by a 5-W Ti:sapphire laser. The target was polarized at a remote "pumping station" outside the SMC cave, and was carried by hand to the muon beam after about 10 h of pumping. The initial polarizations of (40–50)% were largely unaffected [losses < (3–5)%] by the transfer during which the Earth's magnetic field provided a quantization axis. The exponential decay of our target polarization was characterized by a lifetime of nearly 95 h for a cell at room temperature in the pumping station, and 25–30 h for a cell in the beam, where the lifetime was limited by magnetic-field gradients [14] from a quadrupole focusing magnet. The target position was a compromise between minimizing magnetic-field inhomogeneities and achieving a tightly focused muon beam. The use of a separate pumping station reduced our average polarization to 36%, but enabled us to keep our target apparatus particularly simple.

Long cell lifetimes were critical to our efforts, and were achieved through elaborate procedures that were intended to clean both the cell wall and the filling gases. In a distorted-wave Born-approximation calculation similar to that of Shizgal [15], we have computed the relaxation time of ^{3}He due to ^{3}He-^{3}He collisions to be 100 h at 8 atm, an indication that the wall-induced relaxation in our cells was nearly negligible. In a separate experiment, we have performed studies of the relaxation rate of ^{3}He as a function of pressure that confirm our calculations. We thus believe that our target cell lifetimes were near the theoretical limit.

Also critical to the experiment was the μ^- beam tune. It was developed specifically for this experiment [16] to provide a high fraction of stops in our targets, which were extremely small and thin compared to gas targets previously used at LAMPF. Through a combination of focusing and collimation, we achieved a small beam spot with an area of roughly 1 cm^2, and an average muon rate of 1 kHz at a momentum of about 22.5 MeV/c. The beam tune also featured a narrow momentum spread, which was an important factor in stopping about 33% of the muons in the ^{3}He gas.

The geometry of the experiment was quite simple. A pair of thin (40 μm thick) plastic scintillators positioned just in front of the target detected the incoming muons. Two telescopes, located above and below the target, detected the decay electrons from the stopped muons. Each electron telescope contained a pair of scintillators. Beam-line extensions were used to reduce the air through which the muons traveled to less than 2 cm. Gated scalers counted the number of electrons for each telescope that were detected within 4.4 μsec of a muon's arrival.

The polarization of the captured muons was determined from the up-down asymmetry in the gated decay electrons,

$$A_{\text{expt}} = \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}}, \tag{1}$$

where $N_{\uparrow\uparrow}$ ($N_{\uparrow\downarrow}$) is the number of electrons that decayed parallel (antiparallel) to the magnetic holding field. To minimize the effect of drifts in counter gains, the magnetic holding field, and hence the direction of the target spin, was adiabatically rotated every 2 min. It was also possible to choose arbitrarily the direction of the target spins with respect to the magnetic field. The expected sign of A_{expt} is then negative (positive) if the target spins are parallel (antiparallel) to the magnetic field. The experimental asymmetries, adjusted to correspond to the average target polarization of 36%, are displayed in Fig. 1. The experimental asymmetry of approximately 0.3% was obtained in about 100 h of beam time with an error of less than 5%. The cleanliness of these data attests to the power of the rapid polarization reversals possible with laser techniques.

To compute the repolarization ratio P_μ^N, which is defined to be the muon polarization normalized to the nuclear polarization of the ^{3}He target, we first correct the electron telescope counts $N_{\uparrow\uparrow}$ and $N_{\downarrow\uparrow}$ to remove background electrons not arising from decays of tagged muons. This correction is performed using information from the gated and ungated scaler data as well as decay electron time spectra. Next we compute the asymmetry A_c, defined analogously to A_{expt} in (1) but using the corrected electron counts. Finally we compute P_μ^N according to the relation

$$P_\mu^N = A_c / P_{\text{He}} a_e f, \tag{2}$$

where P_{He} is the ^{3}He polarization, a_e is the average analyzing power of the decay electrons, and f is the fraction of decay electrons that come from muons stopped in the ^{3}He. We list the average values for these factors in Table I. However, to obtain our final result, we accounted for the time dependence of P_{He}, f, and the background corrections.

The polarimetry for the target employed a novel frequency shift method [17]. The electron-paramagnetic-resonance (EPR) frequency of Rb atoms in the presence of polarized helium gas is shifted by an amount

$$\Delta\nu = (\tfrac{8}{3}\pi\mu_{\text{He}} P_{\text{He}}[\text{He}])\kappa_0 \gamma_{\text{Rb}}, \tag{3}$$

where the quantity in the parentheses is the classical

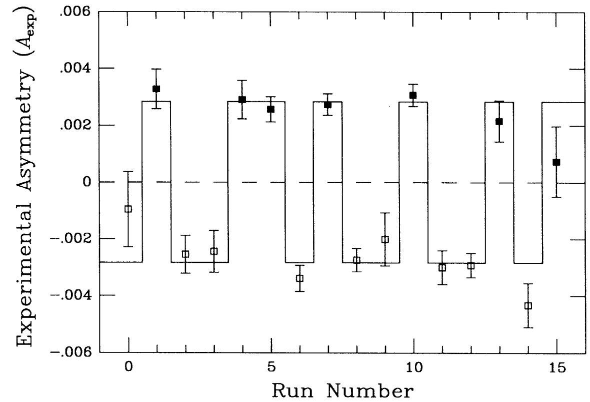

FIG. 1. Raw asymmetries adjusted to a constant helium polarization $P_{\text{He}}=36\%$, and fraction of decay electrons from helium $f=39\%$. As indicated by the solid line, the sign of the asymmetry conforms to that expected from the relative orientation of the target spin to the applied magnetic field.

TABLE I. The average values of the quantities used in determining P_μ^N and their percent contribution to its final error. (The average values are weighted by the muon beam rate.)

Quantity	Value	Error (%)
e^- asymmetry (A_c)	0.0029	± 5.4
Decays from ^{3}He (f)	0.39	± 5.6
^{3}He polarization (P_{He})	0.36	± 6.5
Analyzing power (a_e)	0.29	± 5.5

magnetic induction inside a sphere of ^{3}He with density [He], magnetic moment μ_{He}, and polarization P_{He}. The quantity $\gamma_{\mathrm{Rb}}=4.67\times10^5$ Hz/G is the gyromagnetic ratio of ^{85}Rb, and the dimensionless constant $\kappa_0=6.25\pm0.37$, which characterizes the size of frequency shifts in the Rb-^{3}He system, was measured in a separate set of experiments [18]. While in the beam the cell was held at 50 °C to obtain a Rb number density of 1.3×10^{11} cm^{-3}. A fiber optic carried Rb D_1 light to the cell and the EPR frequency of the Rb was determined every 2 h by measuring the transmission of the D_1 light as a function of the rf applied to the cell [17]. The error in the determination of P_{He} is dominated by the uncertainty in κ_0.

An analysis of the time spectrum of the decay electrons relative to the stopping time of the muon yields values for f. The lifetime of negative muons depends on the atom into which they are captured [19], and thus the shape of the time spectrum depends upon the number of stops in the glass walls relative to the number of ^{3}He stops. Values of f were extracted from the time spectra by fitting a flat background plus three exponentials, corresponding to the lifetimes in helium, oxygen, and silicon. A 5% correction is applied to account for muons captured into the N_2 gas of the target cell. Since the lifetime in ^{3}He (2.2 μsec) is near the value for oxygen (1.8 μsec), the result is extremely sensitive to time spectra distortions. In order to evaluate our ability to extract the correct stopping fraction, we obtained time spectra as a function of beam momentum both for a normal target cell and for a sufficiently thick "background" cell in which all muons stopped in the walls (Fig. 2). Note that f will be larger than the fraction of muon stops in helium because some muons stopped in the glass will undergo nuclear capture. The error in f is dominated by the systematic errors accounting for both the small residual rate-dependent effects (5%) and the uncertainties in correcting for muons captured into the N_2 gas (2.5%).

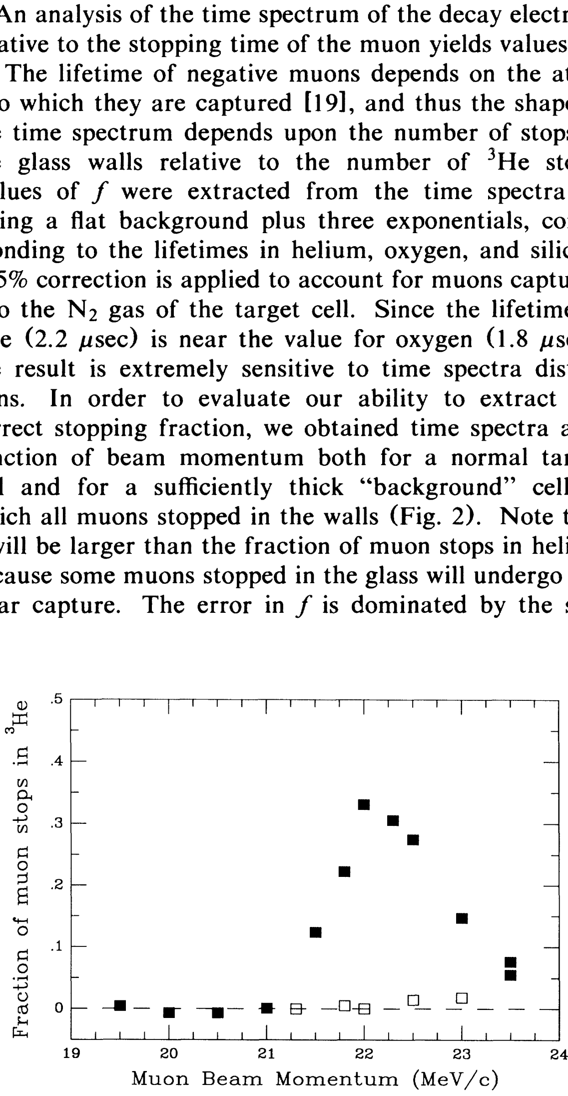

FIG. 2. The fraction of muons stopped in the ^{3}He as a function of beam momentum. The open squares represent a thick-walled target in which all muons stopped in the glass. The solid squares represent a standard target cell. The data points at 23.5 MeV/c were taken at muon rates differing by a factor of 2. The statistical errors are equal to or smaller than the data point size.

The analyzing power of the decay electrons, a_e, was evaluated by a Monte Carlo simulation, which accounted for the dimensions and positions of the electron telescopes, the energy cutoff of the telescopes, the theoretical angular spectrum of decay electrons from a polarized muon [20], and the magnetic-field direction as measured by a Rb magnetometer.

Our final result is $P_\mu^N=0.072\pm0.008$. To compare our results with the work of Kuno, Nagamine, and Yamazaki [8], we need an estimate for the n level at which the hyperfine transition becomes important. The transition rate due to external Auger transitions [21] suggests that n is in the range of 4–5. The calculations of Kuno, Nagamine, and Yamazaki accordingly predict $P_\mu^N \approx 14\%$, a factor of 2 higher than observed. There are several candidates for the cause of the additional depolarization. The most likely possibility is the collisionally induced Stark mixing that has been proposed as the source of the anomalous depolarization that occurs when stopping polarized muon beams in helium. Another possibility is that depolarization occurs in the molecular ion [22] that forms rapidly from the $(\mu^-\,{}^3\mathrm{He})^+$ ion and a ^{3}He atom [21,23]. However, we would expect this effect to be quite small, and we have confirmed this by fitting A_{expt} by the function $A_{\mathrm{expt}}(t)=A_0(1-\alpha t)$, where t is the time following the muon's arrival. We found $\alpha=(-0.05\pm0.06)/\mu$sec, which is consistent with a null effect. On the broader subject of the comparison between ^{3}He and other isotopes, our result is in sharp contrast to the result of $P_\mu^N\approx1$ that was measured by Kadono *et al.* for the case of ^{209}Bi. The large polarization of muons stopped in polarized ^{209}Bi is expected from the calculations of Kuno, Nagamine, and Yamazaki because of the large nuclear spin of $\frac{9}{2}$ and the large value of Z. Future experiments on muon capture into polarized ^{129}Xe (spin $\frac{1}{2}$) and ^{21}Ne (spin $\frac{3}{2}$) should also be possible with this laser technique. The muon cascade in these atoms will be dominated by internal Auger transitions and consequently should occur much more rapidly. This will reduce collisional depolarization, allowing a useful check of the theory of Kuno, Nagamine, and Yamazaki for different spins and Z, and should result in higher polarizations. As in the case of muonic ^{209}Bi, the polarization of muonic ^{21}Ne should be enhanced by hyperfine conversion in the 1s state [8]. Polarized ^{21}Ne might be of interest for use in a time-reversal experiment [24].

In conclusion, our work establishes the value of laser techniques for producing polarized muonic atoms and provides new information about the complex subject of the spin interactions that occur during muonic atom formation. Furthermore, the accuracy with which we were able to extract asymmetries demonstrates the potential of these techniques for future weak-interaction studies. Looking toward the future, we are also pursuing a new method in which muonic ^{3}He is polarized directly by interactions with the laser-polarized Rb vapor. First, the $(\mu^- \, ^3\mathrm{He})^+$ ion picks up a polarized electron from a Rb atom. The spin of the electron is transferred to the $(\mu^- \, ^3\mathrm{He})^+$ "nucleus" via the hyperfine interaction. Additional polarization is attained through spin-exchange collisions of the hydrogenlike $(e^- \mu^- \, ^3\mathrm{He})$ atom with Rb, as has been demonstrated for ordinary hydrogen by Redsun *et al.* [25]. This approach, which we are studying with a modified version of our apparatus, can provide large values for both the vector and tensor polarization of the $(\mu^- \, ^3\mathrm{He})^+$ "nucleus."

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